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A theoretical way to determine gamma-ray mass attenuation coefficients of materials

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Abstract: The gamma-ray mass attenuation coefficients of various absorber materials such as Ag, Al, Au, Bakelite, Cu, Fe, Pb, Plexiglas, Si, Sn, water, and Zn were determined theoretically at different gamma-ray energies and different absorber thicknesses in order to investigate how the number of gamma photons and their energies affect the calculation of mass attenuation coefficients of the absorbers since no study such a comprehensive work here was encountered. For this purpose, the FLUKA Monte Carlo (MC) and XCOM programs were used. Calculated coefficients were compared to the literature values and found to agree well with them. The FLUKA MC program was successful in the calculation of gamma-ray mass attenuation coefficients of materials as was XCOM. The coefficient results were affected by the number of incident gamma photons in the calculation, and a high incident photon number was suggested.

Key words: Gamma-ray mass attenuation coefficient, FLUKA, XCOM

1. Introduction

A gamma ray is removed from a beam entirely by either absorption or scattering. The gamma rays that pass straight through, therefore, are those that have not suffered any interactions at all. They therefore retain their original energy. The total number of gamma rays is, however, reduced by the numbers that have interacted. The attenuation suffered by a gamma-ray beam can be shown, in fact, to be exponential with respect to thickness, i.e.

$$I(x) = I_0 e^{-\mu x} \quad (1)$$

with I_0: incident beam intensity or gamma-ray numbers, x: thickness of absorber, μ: linear attenuation coefficient, I(x): the intensity transmitting through x thickness. The attenuation coefficient is a quantity that is characteristic of the absorbing material [1].

To understand the particle interaction in matter and its kinematics, Monte Carlo (MC) simulation tools are used. FLUKA is one of them and is widely used in many areas such as target shielding, detector design, and medical physics [2,3].

In many scientific, engineering, and medical applications, data on the scattering and absorption of photons (X-rays, gamma-rays, bremsstrahlung) are necessary. Using a personal computer, it is possible to find cross sections and attenuation coefficients for compounds and mixtures for desired energies from 1 keV up to 100 GeV. For this purpose, the XCOM computer program is used [4].

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Linear attenuation coefficient (μ) varies with the density of the absorber, even though the absorber material is the same. Therefore, the mass attenuation coefficient is much more widely used and is defined as

$$\mu_\rho = \mu/\rho, \tag{2}$$

where ρ is the density of the medium [5].

Various studies were carried out about the calculation of gamma-ray attenuation coefficients through theoretical and experimental methods in the 2000s. Some examples in relation with the subject are summarized as follows: Shirmardi et al. investigated gamma-ray mass attenuation coefficients of various barites, concretes, and lead at 0.662, 1.173, and 1.332 MeV energies using MCNP-4C code [6]. The gamma-ray mass attenuation coefficients of different absorber materials for 59.4, 661.6, and 1332.5 keV energies were determined experimentally by Abdel-Rahman et al. [7]. El-Sersy et al. studied the gamma-ray mass attenuation coefficients of various glass systems [8]. Gamma-ray mass attenuation values of different gemstones were calculated by Medhat [9]. Medhat also calculated gamma-ray mass attenuation coefficients for different types of composite materials by means of theoretical and experimental methods and he also compared the obtained coefficient values with XCOM results [10]. Mass attenuation coefficients of gold, bronze, and water at different impurities were calculated by MCNP-4C code and also compared to XCOM values by Esfandiari et al. [11]. Medhat and Wang carried out a study about mass attenuation coefficients of various scintillator materials such as BaF_2, BGO, and NaI(Tl) and compared them with the XCOM results [12]. Some publications are available in relation to the subject of the presented work in the 2010s in Turkey as well. For example, Demir et al. calculated the gamma-ray mass attenuation coefficients of water, concrete, and Bakelite by means of FLUKA, and XCOM was also used to check the accuracy of their results [13]. Gamma-ray linear attenuation coefficients of Plexiglas, Bakelite, and Pb were determined experimentally by Ermis and Celiktas. They also used XCOM for comparison of their results [14]. Akca and Erzeneoglu determined gamma-ray mass attenuation coefficients of some elements at the energy of 59.5 keV experimentally, and they also compared their results with XCOM results [15].

In the present study, gamma-ray mass attenuation coefficients of Pb, Al, Cu, Plexiglas, Bakelite, Ag, Fe, Si, Au, water, Zn, and Sn absorber materials at various thicknesses (1, 3, and 5 cm) were calculated using the FLUKA MC and XCOM programs at eight different gamma-ray energies (59.5, 80.9, 140.5, 36.5, 511.0, 661.6, 1173.2, and 1332.5 keV) since no investigation about the subject through these programs was reported. In addition, the effect of the number of incident gamma photons on the absorbers was investigated differently from the literature ones. Calculated mass attenuation coefficients by choosing various gamma photon numbers and energies were also compared with each other and the literature values. It was found that the calculated mass attenuation coefficients were very close to the literature values. Moreover, the obtained results showed that the mass attenuation coefficients of the materials in various densities and atomic numbers were accurately calculated by means of FLUKA in a wide gamma energy range as an alternative way.

2. Methods

Al, Si, Fe, Cu, Zn, Ag, Sn, Au, Pb, water, Plexiglas ($C_5O_2H_8$), and Bakelite ($(H_2CO)(C_6H_5OH)$) materials were used for the determination of gamma-ray mass attenuation coefficients. In addition, these materials were chosen so that they were the same as those in the literature and it was possible to compare directly the results from FLUKA with them [13–17]. The effect of the number of incident gamma photons on the materials was also investigated in the introduced study, unlike in the previous ones. A simple description about the theoretical procedure is given below.

FLUKA was operated on an Ubuntu (ver. 11.04) operating system. In the MC simulation, the program (ver. 2011.2.15) was used to determine the gamma photon numbers transmitted through the absorber materials. This was done by modifying the FLUKA user routines, which were written in FORTRAN programming language. Even if there are built-in scoring cards to evaluate requested quantities, it has also various routines to retrieve information from different processes. In this work, mgdraw.f routine and its subroutines were used. For FLUKA code, we utilized the advantage of the built-in physics list, PRECISIO physics for FLUKA. More details about this physics list can be found in the literature [2,3]. While performing simulations for each gamma-ray energy impinging on different materials we also took advantage of parallel job executions by using the power of PYTHON scripting language, as well as in the analysis phase of the results. Photons with different energies were tracked as from the surface of the material in the simulation. Afterwards, we determined the number of absorbed photons in the material to evaluate mass attenuation coefficients from the known equation (1). After ten cycles run of each set of different materials and gamma energies, mass attenuation coefficients were calculated from the resulting output files, which were analyzed by a ROOT (ver. 5.34.13) macro. The mean of the ten cycles run of each material was given as calculation result with the standard deviation calculated by the program.

In the FLUKA calculations, the absorber materials were first formed with their thicknesses. Monoenergetic gamma rays with energies of 59.5, 80.9, 140.5, 356.5, 511.0, 661.6, 1173.2, and 1332.5 keV were then sent to each absorber surface. These gamma ray energies were chosen by considering the standard radioactive sources that emit gamma rays. The considered radioactive sources and the energies of gamma rays that are emitted by them are listed in Table 1. The transmitted gamma rays were followed by the program. Finally, the attenuation coefficients were found according to the equations in Eqs. (1) and (2).

Table 1. Considered radioactive sources and their gamma energies.

Radioactive source	^{241}Am	^{133}Ba	^{99m}Tc	^{133}Ba	^{22}Na	^{137}Cs	^{60}Co	^{60}Co
Gamma ray energy (keV)	59.5	80.9	140.5	356.5	511.0	661.6	1173.2	1332.5

The gamma-ray mass attenuation coefficients of the absorbers were calculated using the XCOM program (ver. 3.1) as well. In the program, the absorber material was first chosen from its database. The gamma ray energy was then specified. The gamma-ray mass attenuation coefficient of the chosen material was finally calculated.

The calculated coefficients from the XCOM and FLUKA programs were compared to the literature values. The results are given in the next section.

3. Results and conclusions

In Tables 2–13, the attenuation coefficients calculated through FLUKA and XCOM are presented together with the literature values. Literature lines in Tables 2–13 were formed by using the results in the literature and National Institute of Standard and Technology (NIST) values. The calculated coefficients from FLUKA are given with their standard deviations in these tables.

Calculated mass attenuation coefficients versus gamma photon numbers, the gamma energies, and the absorber thickness of each absorber material are shown in the following figures, respectively (Figures 1–12).

As can be seen in Tables 2–6 and Figures 1–5, the gamma-ray mass attenuation coefficients could be calculated at low energies (e.g., 59.5 and 80.9 keV) for the materials that have low densities and atomic numbers such as water, Bakelite, Plexiglas, Si, and Al. Low-energy gamma rays were also sent to the high-density and high-atomic number materials. These gamma rays were absorbed by the materials. As a result, the calculations could not be carried out at low energies for these materials such as Zn, Sn, Fe, Cu, Ag, Pb, and Au (Tables 7–13 and Figures 6–12). Figures 13–15 are also presented to show clearly the dependencies of mass attenuation coefficients of the materials on the incident gamma energies and the absorber densities.

Table 2. Obtained mass attenuation coefficients according to different photon energies, absorber thicknesses, and photon numbers for Al (ρ = 2.70 g/cm^3).

Method	μ/ρ values according to photon energies (keV)							
	59.5	80.9	140.5	356.5	511.0	661.6	1173.2	1332.5
FLUKA 1000 photons-1 cm absorber	0.283981 ± 0.004287	0.203766 ± 0.002799	0.144665 ± 0.002556	0.098987 ± 0.002280	0.085117 ± 0.002137	0.072636 ± 0.001760	0.056049 ± 0.001161	0.0538760 ± 0.001668
FLUKA 1000 photons-3 cm absorber	0.283640 ± 0.002549	0.203738 ± 0.003527	0.143897 ± 0.002429	0.100129 ± 0.001250	0.083291 ± 0.001053	0.075173 ± 0.000575	0.055361 ± 0.000948	0.052813 ± 0.000874
FLUKA 1000 photons-5 cm absorber	0.285421 ± 0.005167	0.201858 ± 0.003212	0.143036 ± 0.002053	0.098237 ± 0.001535	0.083303 ± 0.000922	0.073340 ± 0.001225	0.056240 ± 0.001118	0.053214 ± 0.001075
FLUKA 5000 photons-1 cm absorber	0.281021 ± 0.001842	0.199657 ± 0.001635	0.141809 ± 0.001111	0.097840 ± 0.001200	0.082750 ± 0.000961	0.074900 ± 0.000704	0.055979 ± 0.000714	0.053915 ± 0.000629
FLUKA 5000 photons-3 cm absorber	0.280975 ± 0.000707	0.201224 ± 0.000962	0.143891 ± 0.000919	0.098016 ± 0.000636	0.083420 ± 0.000370	0.075151 ± 0.000461	0.056368 ± 0.000281	0.052956 ± 0.000474
FLUKA 5000 photons-5 cm absorber	0.279617 ± 0.002037	0.199995 ± 0.001543	0.142583 ± 0.000739	0.097339 ± 0.000408	0.084099 ± 0.000326	0.074995 ± 0.000654	0.056576 ± 0.000297	0.053365 ± 0.000372
FLUKA 10,000 photons-1 cm absorber	0.281654 ± 0.001178	0.200155 ± 0.000903	0.142023 ± 0.000981	0.097016 ± 0.000752	0.083907 ± 0.000573	0.074910 ± 0.000431	0.056125 ± 0.000384	0.053728 ± 0.000398
FLUKA 10,000 photons-3 cm absorber	0.282108 ± 0.000676	0.201419 ± 0.000639	0.143104 ± 0.000390	0.097439 ± 0.000362	0.083226 ± 0.000354	0.074753 ± 0.000344	0.056431 ± 0.000193	0.053250 ± 0.000269
FLUKA 10,000 photons-5 cm absorber	0.279833 ± 0.001559	0.198132 ± 0.000820	0.142328 ± 0.000599	0.097689 ± 0.000251	0.084035 ± 0.000250	0.075100 ± 0.000371	0.056515 ± 0.000255	0.052978 ± 0.000299
XCOM	0.2810	0.1998	0.1420	0.0972	0.0836	0.0746	0.0567	0.0532
Literature	0.2700 (for 60 keV) [18]	0.1980 (for 80 keV) [18]	0.1380 (for 150 keV) [18]	0.1040 (for 300 keV) [18]	0.0844 (for 500 keV) [18]	0.0742 [21]	0.0567 [20]	0.0532 [21]

Table 3. Obtained mass attenuation coefficients according to different photon energies, absorber thicknesses, and photon numbers for Si (ρ = 2.33 g/cm^3).

Method	μ/ρ values according to photon energies (keV)							
	59.5	80.9	140.5	356.5	511.0	661.6	1173.2	1332.5
FLUKA 1000 photons-1 cm absorber	0.321605 ± 0.000378	0.218483 ± 0.003109	0.150432 ± 0.003120	0.098365 ± 0.002522	0.084752 ± 0.002196	0.076691 ± 0.001312	0.056590 ± 0.001211	0.0531440 ± 0.001741
FLUKA 1000 photons-3 cm absorber	0.335301 ± 0.003354	0.221394 ± 0.002665	0.148423 ± 0.001797	0.099938 ± 0.001364	0.084838 ± 0.001415	0.077892 ± 0.001397	0.058358 ± 0.001369	0.054982 ± 0.000767
FLUKA 1000 photons-5 cm absorber	0.331774 ± 0.005104	0.225493 ± 0.002636	0.149829 ± 0.001788	0.100887 ± 0.001606	0.086707 ± 0.001018	0.075904 ± 0.000863	0.059032 ± 0.000760	0.054509 ± 0.000922
FLUKA 5000 photons-1 cm absorber	0.320915 ± 0.001346	0.218939 ± 0.001185	0.148668 ± 0.001286	0.100197 ± 0.000748	0.085863 ± 0.000970	0.077501 ± 0.000739	0.058356 ± 0.000704	0.054749 ± 0.000479
FLUKA 5000 photons-3 cm absorber	0.327883 ± 0.001960	0.221636 ± 0.001036	0.149537 ± 0.001245	0.100389 ± 0.000651	0.087577 ± 0.000598	0.077615 ± 0.000422	0.059036 ± 0.000329	0.054742 ± 0.000413
FLUKA 5000 photons-5 cm absorber	0.330500 ± 0.001450	0.200587 ± 0.001251	0.149739 ± 0.000757	0.101152 ± 0.000426	0.086164 ± 0.000432	0.076486 ± 0.000288	0.058486 ± 0.000202	0.054843 ± 0.000331
FLUKA 10,000 photons-1 cm absorber	0.324406 ± 0.001505	0.220847 ± 0.000983	0.149701 ± 0.001003	0.100487 ± 0.000495	0.086457 ± 0.000733	0.07716 ± 0.000614	0.058342 ± 0.000371	0.055158 ± 0.000317
FLUKA 10,000 photons-3 cm absorber	0.327255 ± 0.001359	0.222515 ± 0.000942	0.150227 ± 0.000555	0.100963 ± 0.000540	0.086795 ± 0.000499	0.076976 ± 0.000412	0.058891 ± 0.000305	0.054959 ± 0.000273
FLUKA 10,000 photons-5 cm absorber	0.327871 ± 0.001375	0.219549 ± 0.000929	0.149627 ± 0.000467	0.101349 ± 0.000338	0.086604 ± 0.000391	0.077316 ± 0.000378	0.058792 ± 0.000283	0.054843 ± 0.000138
XCOM	0.3248	0.2203	0.1495	0.1008	0.0866	0.0773	0.0587	0.0550
Literature	0.3150 (for 60 keV) [18]	0.2210 (for 80 keV) [18]	0.1440 (for 150 keV) [18]	0.1080 (for 300 keV) [18]	0.0873 (for 500 keV) [18]	0.0776 [20]	0.0589 [20]	0.0551 [20]

The plots of calculated mass attenuation coefficients versus gamma (i.e. photon) energies and absorber densities are shown in Figures 13–15 for 5000 gamma photons together with different absorber thicknesses.

Table 4. Obtained mass attenuation coefficients according to different photon energies, absorber thicknesses, and photon numbers for Fe ($\rho = 7.87$ g/cm^3).

Method	μ/ρ values according to photon energies (keV)							
	59.5	80.9	140.5	356.5	511.0	661.6	1173.2	1332.5
FLUKA 1000 photons-1 cm absorber	-	-	0.211318 ± 0.001962	0.100082 ± 0.001453	0.082882 ± 0.001473	0.073983 ± 0.000885	0.055917 ± 0.000537	0.052917 ± 0.000574
FLUKA 1000 photons-3 cm absorber	-	-	0.220522 ± 0.007769	0.100414 ± 0.001726	0.083595 ± 0.000908	0.074226 ± 0.000845	0.055586 ± 0.000772	0.052291 ± 0.001056
FLUKA 1000 photons-5 cm absorber	-	-	-	0.104621 ± 0.002498	0.083276 ± 0.000673	0.072585 ± 0.001211	0.056293 ± 0.000491	0.052791 ± 0.000992
FLUKA 5000 photons-1 cm absorber	-	0.570789 ± 0.004674	0.213490 ± 0.000838	0.099653 ± 0.000465	0.08352 ± 0.000423	0.073864 ± 0.000508	0.055789 ± 0.000494	0.051698 ± 0.000348
FLUKA 5000 photons-3 cm absorber	-	-	0.214999 ± 0.002397	0.099716 ± 0.000472	0.083486 ± 0.000401	0.072798 ± 0.000438	0.055451 ± 0.000178	0.051526 ± 0.000185
FLUKA 5000 photons-5 cm absorber	-	-	0.200193 ± 0.005447	0.102251 ± 0.000741	0.083181 ± 0.000374	0.073606 ± 0.000322	0.055304 ± 0.000412	0.051791 ± 0.000475
FLUKA 10,000 photons-1 cm absorber	0.935772 ± 0.155962	0.578861 ± 0.003918	0.213844 ± 0.000531	0.100393 ± 0.000481	0.083873 ± 0.000317	0.073388 ± 0.000267	0.055139 ± 0.000256	0.05190 ± 0.000254
FLUKA 10,000 photons-3 cm absorber	-	-	0.214706 ± 0.002557	0.100064 ± 0.000288	0.083021 ± 0.000295	0.07318 ± 0.000290	0.055327 ± 0.000189	0.051791 ± 0.000235
FLUKA 10,000 photons-5 cm absorber	-	-	0.214706 ± 0.002557	0.100064 ± 0.000288	0.083021 ± 0.000295	0.07318 ± 0.000290	0.055327 ± 0.000189	0.051791 ± 0.000235
XCOM	1.2310	0.0580	0.2136	0.0998	0.0832	0.0734	0.0552	0.0518
Literature	1.2000 (for 60 keV) [18]	0.5950 (for 80 keV) [18]	0.1960 (for 150 keV) [18]	0.1101 (for 300 keV) [18]	0.0840 (for 500 keV) [18]	0.0731 [20]	0.0557 [20]	0.0521 [20]

The calculated coefficients vs. incident gamma energies and absorber densities can be seen in the tables for different gamma photon numbers and absorber thicknesses also.

Table 5. Obtained mass attenuation coefficients according to different photon energies, absorber thicknesses, and photon numbers for Cu (ρ=8.96 g/cm^3).

Method	μ/ρ values according to photon energies (keV)							
	59.5	80.9	140.5	356.5	511.0	661.6	1173.2	1332.5
FLUKA 1000 photons-1 cm absorber	-	0.718699 ± 0.018699	0.245144 ± 0.002799	0.100231 ± 0.000995	0.084062 ± 0.000904	0.072401 ± 0.000981	0.053860 ± 0.000722	0.050332 ± 0.000784
FLUKA 1000 photons-3 cm absorber	-	-	0.236988 ± 0.005780	0.099177 ± 0.000836	0.083250 ± 0.000923	0.071717 ± 0.000694	0.054134 ± 0.000661	0.050332 ± 0.000628
FLUKA 1000 photons-5 cm absorber	-	-	-	0.099692 ± 0.001750	0.084012 ± 0.001195	0.073276 ± 0.000724	0.054498 ± 0.000784	0.049831 ± 0.000588
FLUKA 5000 photons-1 cm absorber	-	0.743044 ± 0.010881	0.243233 ± 0.001276	0.100080 ± 0.000470	0.082576 ± 0.000713	0.072587 ± 0.000516	0.054004 ± 0.000384	0.050313 ± 0.000311
FLUKA 5000 photons-3 cm absorber	-	-	0.251377 ± 0.005156	0.100193 ± 0.000787	0.082520 ± 0.000445	0.072292 ± 0.000351	0.054389 ± 0.000289	0.050450 ± 0.000399
FLUKA 5000 photons-5 cm absorber	-	-	-	0.100235 ± 0.000813	0.083507 ± 0.000576	0.072961 ± 0.000259	0.054792 ± 0.000300	0.050870 ± 0.000276
FLUKA 10,000 photons-1 cm absorber	-	0.752312 ± 0.009493	0.244428 ± 0.001236	0.100581 ± 0.000372	0.082396 ± 0.000410	0.072688 ± 0.000265	0.054310 ± 0.000345	0.050761 ± 0.000340
FLUKA 10,000 photons-3 cm absorber	-	-	0.244130 ± 0.002910	0.100553 ± 0.000544	0.082229 ± 0.000454	0.072886 ± 0.000341	0.054352 ± 0.000163	0.050543 ± 0.000271
FLUKA 10,000 photons-5 cm absorber	-	-	0.190116 ± 0.000000	0.101102 ± 0.000483	0.083051 ± 0.000321	0.072697 ± 0.000419	0.054432 ± 0.000230	0.050811 ± 0.000231
XCOM	1.6290	0.7426	0.2446	0.1005	0.0827	0.0726	0.0543	0.0509
Literature	1.5800 (for 60 keV) [18]	0.7620 (for 80 keV) [18]	0.2220 (for 150 keV) [18]	0.1120 (for 300 keV) [18]	0.0834 (For 500 keV) [18]	0.0721 [21]	0.059 (for 1000 keV) [19]	0.0506 [21]

As the incident gamma energies were increased, the calculated mass attenuation coefficient values decreased for all absorber thicknesses as expected (Figures 16–18).

Table 6. Obtained mass attenuation coefficients according to different photon energies, absorber thicknesses, and photon numbers for Zn ($\rho = 7.13$ g/cm^3).

Method	μ/ρ values according to photon energies (keV)							
	59.5	80.9	140.5	356.5	511.0	661.6	1173.2	1332.5
FLUKA 1000 photons-1 cm absorber	-	0.840444 ± 0.022557	0.259286 ± 0.003732	0.100364 ± 0.001134	0.084897 ± 0.001057	0.073716 ± 0.000128	0.056459 ± 0.000812	0.051237 ± 0.000450
FLUKA 1000 photons-3 cm absorber	-	-	0.262983 ± 0.006277	0.105663 ± 0.001297	0.083907 ± 0.001025	0.073301 ± 0.000605	0.055440 ± 0.000655	0.053441 ± 0.000441
FLUKA 1000 photons-5 cm absorber	-	-	0.135579 ± 0.029586	0.10155 ± 0.002264	0.082634 ± 0.000607	0.074046 ± 0.000581	0.053997 ± 0.000412	0.051624 ± 0.000788
FLUKA 5000 photons-1 cm absorber	-	0.801708 ± 0.012338	0.257797 ± 0.001513	0.101214 ± 0.000448	0.083330 ± 0.000577	0.073961 ± 0.000366	0.054785 ± 0.000438	0.051559 ± 0.000370
FLUKA 5000 photons-3 cm absorber	-	-	0.255923 ± 0.002000	0.103735 ± 0.000764	0.083789 ± 0.000545	0.072995 ± 0.000334	0.054467 ± 0.000257	0.051914 ± 0.000337
FLUKA 5000 photons-5 cm absorber	-	-	0.238811 ± 0.000000	0.101658 ± 0.000673	0.083904 ± 0.000683	0.073168 ± 0.000351	0.053847 ± 0.000310	0.050745 ± 0.000323
FLUKA 10,000 photons-1 cm absorber	-	0.819272 ± 0.009666	0.259107 ± 0.001310	0.101632 ± 0.000404	0.083505 ± 0.000401	0.073534 ± 0.000241	0.054681 ± 0.000258	0.051207 ± 0.000445
FLUKA 10,000-3 cm absorber	-	-	0.258950 ± 0.002439	0.102542 ± 0.000602	0.083409 ± 0.000386	0.073092 ± 0.000280	0.054607 ± 0.000183	0.051560 ± 0.000309
FLUKA 10,000 photons-5 cm absorber	-	-	0.254359 ± 0.002591	0.101854 ± 0.000538	0.083501 ± 0.000412	0.073347 ± 0.000303	0.054217 ± 0.000186	0.050911 ± 0.000218
XCOM	1.8000	0.8138	0.2595	0.1021	0.0835	0.0732	0.0547	0.0512
Literature	1.1760 (for 60 keV) [19]	0.8364 (for 80 keV) [19]	0.2341 (for 150 keV) [19]	0.1141 (for 300 keV) [19]	0.0845 (for 500 keV) [19]	0.0730 [20]	0.0548 [20]	0.0511 [20]

Table 7. Obtained mass attenuation coefficients according to different photon energies, absorber thicknesses, and photon numbers for Ag ($\rho = 10.50$ g/cm^3).

Method	μ/ρ values according to photon energies (keV)							
	59.5	80.9	140.5	356.5	511.0	661.6	1173.2	1332.5
FLUKA 1000 photons-1 cm absorber	-	-	0.556961 ± 0.063903	0.128409 ± 0.001299	0.09376 ± 0.000953	0.075344 ± 0.000837	0.053778 ± 0.000945	0.049952 ± 0.000838
FLUKA 1000 photons-3 cm absorber	-	-	-	0.131149 ± 0.002877	0.090413 ± 0.000958	0.076566 ± 0.000783	0.054165 ± 0.000741	0.05077 ± 0.000851
FLUKA 1000 photons-5 cm absorber	-	-	-	0.122882 ± 0.002480	0.091818 ± 0.002098	0.073897 ± 0.001471	0.053887 ± 0.000555	0.051081 ± 0.000643
FLUKA 5000 photons-1 cm absorber	-	-	0.633988 ± 0.016238	0.12685 ± 0.000922	0.0919941 ± 0.000736	0.075509 ± 0.000336	0.054069 ± 0.000313	0.050474 ± 0.000264
FLUKA 5000 photons-3 cm absorber	-	-	-	0.126153 ± 0.001509	0.092032 ± 0.000705	0.075645 ± 0.000349	0.054001 ± 0.000388	0.050451 ± 0.000284
FLUKA 5000 photons-5 cm absorber	-	-	-	0.128782 ± 0.002771	0.092832 ± 0.001113	0.075857 ± 0.000655	0.05393 ± 0.000376	0.050636 ± 0.000372
FLUKA 10,000 photons-1 cm absorber	-	-	0.628484 ± 0.009588	0.126359 ± 0.000663	0.091676 ± 0.000605	0.075469 ± 0.000152	0.054014 ± 0.000247	0.050212 ± 0.000204
FLUKA 10,000 photons-3 cm absorber	-	-	-	0.127327 ± 0.001045	0.091834 ± 0.000483	0.075977 ± 0.000228	0.054022 ± 0.000237	0.050298 ± 0.000131
FLUKA 10,000 photons-5 cm absorber	-	-	-	0.128293 ± 0.001188	0.091956 ± 0.000811	0.076394 ± 0.000592	0.053791 ± 0.000274	0.050467 ± 0.000249
XCOM	5.8990	2.5720	0.6311	0.1272	0.0916	0.0763	0.0539	0.0504
Literature	5.7660 (for 60 keV) [19]	2.6510 (for 80 keV) [19]	0.5426 (for 150 keV) [19]	0.1560 (for 300 keV) [19]	0.0932 (for 500 keV) [19]	0.0815 (for 600 keV) [19]	0.0592 (for 1000 keV) [19]	0.0521 (for 1250 keV) [19]

Table 8. Obtained mass attenuation coefficients according to different photon energies, absorber thicknesses, and photon numbers for Sn ($\rho = 7.31$ g/cm^3).

Method	μ/ρ values according to photon energies (keV)							
	59.5	80.9	140.5	356.5	511.0	661.6	1173.2	1332.5
FLUKA 1000 photons-1 cm absorber	-	-	0.733467 ± 0.027594	0.133468 ± 0.001304	0.091873 ± 0.001571	0.074907 ± 0.001330	0.052682 ± 0.000850	0.047898 ± 0.000792
FLUKA 1000 photons-3 cm absorber	-	-	-	0.133103 ± 0.000954	0.093529 ± 0.001208	0.076084 ± 0.000648	0.051873 ± 0.000549	0.049301 ± 0.000642
FLUKA 1000 photons-5 cm absorber	-	-	-	0.13056 ± 0.002856	0.091056 ± 0.001271	0.075536 ± 0.000657	0.052957 ± 0.000543	0.049448 ± 0.000556
FLUKA 5000 photons-1 cm absorber	-	-	0.701937 ± 0.007946	0.131631 ± 0.000912	0.092591 ± 0.000694	0.075588 ± 0.000376	0.052884 ± 0.000396	0.049445 ± 0.000423
FLUKA 5000 photons-3 cm absorber	-	-	-	0.130877 ± 0.000852	0.091921 ± 0.000560	0.075763 ± 0.000244	0.052359 ± 0.000352	0.049311 ± 0.000146
FLUKA 5000 photons-5 cm absorber	-	-	-	0.129159 ± 0.000979	0.091697 ± 0.000488	0.075149 ± 0.000453	0.052422 ± 0.000277	0.04926 ± 0.000339
FLUKA 10,000 photons-1 cm absorber	-	-	0.710000 ± 0.007270	0.131286 ± 0.000597	0.092385 ± 0.000346	0.075115 ± 0.000342	0.052755 ± 0.000292	0.049456 ± 0.000297
FLUKA 10,000 photons-3 cm absorber	-	-	-	0.130878 ± 0.000634	0.091593 ± 0.000359	0.075597 ± 0.000146	0.052579 ± 0.000232	0.049316 ± 0.000152
FLUKA 10,000 photons-5 cm absorber	-	-	-	0.12972 ± 0.001093	0.091388 ± 0.000385	0.075051 ± 0.000358	0.05264 ± 0.000171	0.049077 ± 0.000141
XCOM	6.1750	2.9390	0.7112	0.1313	0.0920	0.0756	0.0527	0.0492
Literature	6.4700 (for 60 keV) [18]	2.9800 (for 80 keV) [18]	0.6010 (for 150 keV) [18]	0.1163 (for 300 keV) [18]	0.0924 (for 500 keV) [18]	0.0740 [21]	0.0580 (for 1000 keV) [19]	0.0488 [21]

Table 9. Obtained mass attenuation coefficients according to different photon energies, absorber thicknesses, and photon numbers for Au (ρ = 19.32 g/cm^3).

Method	μ/ρ values according to photon energies (keV)							
	59.5	80.9	140.5	356.5	511.0	661.6	1173.2	1332.5
FLUKA 1000 photons-1 cm absorber	-	-	-	0.265464 ± 0.005082	0.147888 ± 0.002247	0.107166 ± 0.001320	0.061757 ± 0.000685	0.060691 ± 0.002053
FLUKA 1000 photons-3 cm absorber	-	-	-	-	-	0.100948 ± 0.003576	0.060557 ± 0.000660	0.054633 ± 0.000904
FLUKA 1000 photons-5 cm absorber	-	-	-	-	-	-	0.060557 ± 0.002053	0.059213 ± 0.001853
FLUKA 5000 photons-1 cm absorber	-	-	-	0.264691 ± 0.003476	0.147084 ± 0.000969	0.104422 ± 0.000614	0.060439 ± 0.000375	0.055485 ± 0.000289
FLUKA 5000 photons-3 cm absorber	-	-	-	-	0.112573 ± 0.018924	0.107762 ± 0.001964	0.060841 ± 0.000530	0.055291 ± 0.000419
FLUKA 5000 photons-5 cm absorber	-	-	-	-	-	0.025733 ± 0.013117	0.061306 ± 0.001253	0.055469 ± 0.000925
FLUKA 10,000 photons-1 cm absorber	-	-	-	0.263712 ± 0.002620	0.146705 ± 0.000570	0.104870 ± 0.000478	0.060659 ± 0.000285	0.055397 ± 0.000204
FLUKA 10,000 photons-3 cm absorber	-	-	-	-	0.143899 ± 0.003768	0.106264 ± 0.001423	0.060651 ± 0.000305	0.055138 ± 0.000245
FLUKA 10,000 photons-5 cm absorber	-	-	-	-	-	0.089659 ± 0.001895	0.060850 ± 0.000722	0.055160 ± 0.000572
XCOM	4.6270	8.8530	2.1890	0.0267	0.1482	0.1060	0.0607	0.0554
Literature	4.5280 (for 60 keV) [19]	2.1850 (for 80 keV) [19]	1.8600 (for 150 keV) [19]	0.3744 (for 300 keV) [19]	0.1530 (for 500 keV) [19]	0.1194 (for 600 keV) [19]	0.0695 (for 1000 keV) [19]	0.0579 (for 1250 keV) [19]

Table 10. Obtained mass attenuation coefficients according to different photon energies, absorber thicknesses, and photon numbers for Pb ($\rho = 11.34$ g/cm^3).

Method	μ/ρ values according to photon energies (keV)							
	59.5	80.9	140.5	356.5	511.0	661.6	1173.2	1332.5
FLUKA 1000 photons-1 cm absorber	-	-	-	0.290717 ± 0.004811	0.158061 ± 0.001890	0.109869 ± 0.000852	0.062378 ± 0.000751	0.056656 ± 0.001014
FLUKA 1000 photons-3 cm absorber	-	-	-	-	0.164681 ± 0.003038	0.111986 ± 0.001703	0.062280 ± 0.000915	0.055926 ± 0.000528
FLUKA 1000 photons-5 cm absorber	-	-	-	-	0.109647 ± 0.012183	0.104507 ± 0.002560	0.061679 ± 0.001353	0.056016 ± 0.001060
FLUKA 5000 photons-1 cm absorber	-	-	-	0.283998 ± 0.001694	0.154518 ± 0.000856	0.109804 ± 0.000556	0.061279 ± 0.000358	0.056267 ± 0.000400
FLUKA 5000 photons-3 cm absorber	-	-	-	0.200287 ± 0.033381	0.159842 ± 0.002223	0.109342 ± 0.000979	0.061643 ± 0.000369	0.056212 ± 0.000372
FLUKA 5000 photons-5 cm absorber	-	-	-	-	0.147770 ± 0.001630	0.108964 ± 0.001518	0.061725 ± 0.000419	0.055734 ± 0.000401
FLUKA 10,000 photons-1 cm absorber	-	-	-	0.283886 ± 0.001246	0.154671 ± 0.000498	0.109527 ± 0.000303	0.061359 ± 0.000329	0.056005 ± 0.000232
FLUKA 10,000 photons-3 cm absorber	-	-	-	0.265466 ± 0.003622	0.157169 ± 0.001781	0.109676 ± 0.000915	0.061732 ± 0.000164	0.056070 ± 0.000163
FLUKA 10,000 photons-5 cm absorber	-	-	-	-	0.150722 ± 0.002350	0.108945 ± 0.001082	0.061899 ± 0.000316	0.055670 ± 0.000200
XCOM	5.1290	2.3530	2.3690	0.2866	0.1562	0.1102	0.0617	0.0561
Literature	3.5500 (for 60 keV) [19]	1.6600 (for 80 keV) [19]	1.9200 (for 150 keV) [19]	0.3770 (for 300 keV) [19]	0.1520 (for 500 keV) [18]	0.1072 [21]	0.0615 [20]	0.0553 [21]

Table 11. Obtained mass attenuation coefficients according to different photon energies, absorber thicknesses, and photon numbers for water ($\rho = 1$ g/cm^3).

Method	μ/ρ values according to photon energies (keV)							
	59.5	80.9	140.5	356.5	511.0	661.6	1173.2	1332.5
FLUKA 1000 photons-1 cm absorber	0.209802 ± 0.003900	0.185007 ± 0.005233	0.147508 ± 0.003395	0.119168 ± 0.003228	0.106011 ± 0.004598	0.088796 ± 0.004062	0.069304 ± 0.003684	0.059983 ± 0.002155
FLUKA 1000 photons-3 cm absorber	0.208916 ± 0.002830	0.186799 ± 0.003665	0.15199 ± 0.002634	0.113595 ± 0.001743	0.095332 ± 0.001051	0.084650 ± 0.001497	0.067157 ± 0.001478	0.059937 ± 0.001460
FLUKA 1000 photons-5 cm absorber	0.207386 ± 0.003001	0.184706 ± 0.002541	0.153371 ± 0.001567	0.112155 ± 0.001904	0.094587 ± 0.001361	0.086754 ± 0.001801	0.064617 ± 0.001035	0.062835 ± 0.001146
FLUKA 5000 photons-1 cm absorber	0.208491 ± 0.001777	0.184651 ± 0.001184	0.155786 ± 0.002129	0.114925 ± 0.001347	0.098559 ± 0.002083	0.088362 ± 0.001567	0.066916 ± 0.001252	0.061709 ± 0.000939
FLUKA 5000 photons-3 cm absorber	0.206755 ± 0.001319	0.181655 ± 0.001577	0.152715 ± 0.000962	0.112126 ± 0.001265	0.095825 ± 0.000882	0.085360 ± 0.000778	0.065839 ± 0.000665	0.061846 ± 0.000804
FLUKA 5000 photons-5 cm absorber	0.206587 ± 0.000683	0.182803 ± 0.001226	0.153491 ± 0.000718	0.111211 ± 0.000456	0.095827 ± 0.000539	0.085079 ± 0.000807	0.065572 ± 0.000422	0.060758 ± 0.000718
FLUKA 10,000 photons-1 cm absorber	0.206429 ± 0.001310	0.182837 ± 0.001276	0.154084 ± 0.001629	0.111843 ± 0.001157	0.096815 ± 0.001230	0.086532 ± 0.001010	0.065577 ± 0.000789	0.060773 ± 0.000923
FLUKA 10,000 photons-3 cm absorber	0.207218 ± 0.001254	0.182043 ± 0.000984	0.152980 ± 0.000480	0.111153 ± 0.000523	0.095747 ± 0.000554	0.085754 ± 0.000657	0.065686 ± 0.000425	0.061287 ± 0.000510
FLUKA 10,000 photons-5 cm absorber	0.20660 ± 0.000548	0.183054 ± 0.000702	0.153544 ± 0.000443	0.110441 ± 0.000560	0.095821 ± 0.000564	0.085734 ± 0.000579	0.065114 ± 0.000423	0.060799 ± 0.000438
XCOM	0.2067	0.1829	0.1537	0.1111	0.0959	0.0857	0.0653	0.0611
Literature	0.2040 (for 60 keV) [18]	0.1830 (for 80 keV) [18]	0.1510 (for 150 keV) [18]	0.1190 (for 300 keV) [18]	0.0966 (for 500 keV) [18]	0.0896 (for 600 keV) [18]	0.0707 (for 1000 keV) [19]	0.0632 (for 1250 keV) [19]

Table 12. Obtained mass attenuation coefficients according to different photon energies, absorber thicknesses, and photon numbers for Plexiglas (ρ = 1.17 g/cm^3).

Method	μ/ρ values according to photon energies (keV)							
	59.5	80.9	140.5	356.5	511.0	661.6	1173.2	1332.5
FLUKA 1000 photons-1 cm absorber	0.198849 ± 0.003850	0.182272 ± 0.003249	0.155308 ± 0.005539	0.110831 ± 0.001773	0.093450 ± 0.003607	0.085624 ± 0.002135	0.066844 ± 0.002216	0.062588 ± 0.001419
FLUKA 1000 photons-3 cm absorber	0.196347 ± 0.002751	0.179473 ± 0.002479	0.149440 ± 0.002266	0.110468 ± 0.001740	0.092981 ± 0.002548	0.085734 ± 0.001283	0.064599 ± 0.001673	0.061324 ± 0.001145
FLUKA 1000 photons-5 cm absorber	0.200642 ± 0.002880	0.179238 ± 0.002550	0.149161 ± 0.001903	0.111238 ± 0.000708	0.093549 ± 0.000874	0.084257 ± 0.001626	0.064199 ± 0.001673	0.058764 ± 0.001001
FLUKA 5000 photons-1 cm absorber	0.197359 ± 0.002419	0.181047 ± 0.001644	0.155317 ± 0.001037	0.110703 ± 0.000968	0.095584 ± 0.001136	0.083929 ± 0.001294	0.064424 ± 0.000962	0.060983 ± 0.000847
FLUKA 5000 photons-3 cm absorber	0.195268 ± 0.000988	0.176067 ± 0.001111	0.149041 ± 0.000771	0.109649 ± 0.000737	0.094843 ± 0.000962	0.084967 ± 0.000559	0.064498 ± 0.000826	0.059943 ± 0.000666
FLUKA 5000 photons-5 cm absorber	0.197556 ± 0.001316	0.177376 ± 0.000775	0.151245 ± 0.000931	0.111533 ± 0.000518	0.093442 ± 0.000530	0.084375 ± 0.000583	0.064951 ± 0.000349	0.059796 ± 0.000384
FLUKA 10,000 photons-1 cm absorber	0.195626 ± 0.001251	0.179201 ± 0.000892	0.153425 ± 0.001228	0.110557 ± 0.000954	0.094892 ± 0.000617	0.083849 ± 0.000947	0.065010 ± 0.000480	0.059908 ± 0.000585
FLUKA 10,000 photons-3 cm absorber	0.195296 ± 0.000479	0.176419 ± 0.000601	0.149510 ± 0.000672	0.110118 ± 0.000720	0.094441 ± 0.000623	0.084903 ± 0.000608	0.064403 ± 0.000571	0.059849 ± 0.000725
FLUKA 10,000 photons-5 cm absorber	0.196513 ± 0.000743	0.177848 ± 0.000613	0.151002 ± 0.000683	0.110501 ± 0.000323	0.094393 ± 0.000427	0.084852 ± 0.000385	0.064586 ± 0.000341	0.060154 ± 0.000296
XCOM	0.1930	0.1745	0.1486	0.1079	0.0932	0.0833	0.0634	0.0594
Literature	0.1924 (for 60 keV) [19]	0.1751 (for 80 keV) [19]	0.1456 (for 150 keV) [19]	0.1152 (for 300 keV) [19]	0.0941 (for 500 keV) [19]	0.0891 [14]	0.0687 (for 1000 keV) [19]	0.0614 (for 1250 keV) [19]

Table 13. Obtained mass attenuation coefficients according to different photon energies, absorber thicknesses, and photon numbers for Bakelite ($\rho = 1.15$ g/cm^3).

Method	μ/ρ values according to photon energies (keV)							
	59.5	80.9	140.5	356.5	511.0	661.6	1173.2	1332.5
FLUKA 1000 photons-1 cm absorber	0.186290 ± 0.003951	0.173370 ± 0.003257	0.144936 ± 0.002374	0.104300 ± 0.002584	0.085916 ± 0.001925	0.085604 ± 0.001942	0.063637 ± 0.002263	0.060333 ± 0.002747
FLUKA 1000 photons-3 cm absorber	0.189309 ± 0.002341	0.170918 ± 0.001934	0.145750 ± 0.000963	0.105078 ± 0.001804	0.092427 ± 0.000998	0.082345 ± 0.001671	0.062830 ± 0.000811	0.056674 ± 0.001187
FLUKA 1000 photons-5 cm absorber	0.188218 ± 0.002608	0.175825 ± 0.001716	0.148819 ± 0.002074	0.105804 ± 0.001105	0.092620 ± 0.001130	0.081341 ± 0.001571	0.064812 ± 0.001236	0.057979 ± 0.000728
FLUKA 5000 photons-1 cm absorber	0.188018 ± 0.001780	0.173189 ± 0.002147	0.147829 ± 0.001452	0.106373 ± 0.001355	0.092670 ± 0.001356	0.082348 ± 0.001154	0.064080 ± 0.001050	0.058528 ± 0.000686
FLUKA 5000 photons -3 cm absorber	0.187412 ± 0.000852	0.170279 ± 0.001081	0.145561 ± 0.000744	0.106364 ± 0.000732	0.091970 ± 0.000681	0.083908 ± 0.000645	0.062524 ± 0.000419	0.057714 ± 0.000780
FLUKA 5000 photons-5 cm absorber	0.187930 ± 0.000786	0.173398 ± 0.000873	0.146641 ± 0.001182	0.106489 ± 0.000355	0.091845 ± 0.000545	0.082667 ± 0.001050	0.063289 ± 0.000428	0.058782 ± 0.000317
FLUKA 10,000 photons-1 cm absorber	0.185770 ± 0.001516	0.170612 ± 0.001711	0.146759 ± 0.001272	0.106559 ± 0.000830	0.093320 ± 0.001012	0.082686 ± 0.000835	0.062541 ± 0.000659	0.058903 ± 0.000658
FLUKA 10,000 photons-3 cm absorber	0.188219 ± 0.000695	0.0171284 ± 0.000808	0.145505 ± 0.000331	0.106083 ± 0.000558	0.091505 ± 0.000413	0.082915 ± 0.000554	0.063117 ± 0.000421	0.058098 ± 0.000409
FLUKA 10,000 photons-5 cm absorber	0.187126 ± 0.000606	0.172477 ± 0.000621	0.146625 ± 0.000527	0.106411 ± 0.000384	0.091936 ± 0.000367	0.082048 ± 0.000499	0.062865 ± 0.000270	0.059251 ± 0.000361
XCOM	0.1897	0.1718	0.1464	0.1063	0.0919	0.0821	0.0625	0.0586
Literature	0.1866 (for 60 keV) [19]	0.1707 (for 80 keV) [19]	0.1424 (for 150 keV) [19]	0.1127 (for 300 keV) [19]	0.0921 (for 500 keV) [19]	0.0850 (for 600 keV) [19]	0.0672 (for 1000 keV) [19]	0.0601 (for 1250 keV) [19]

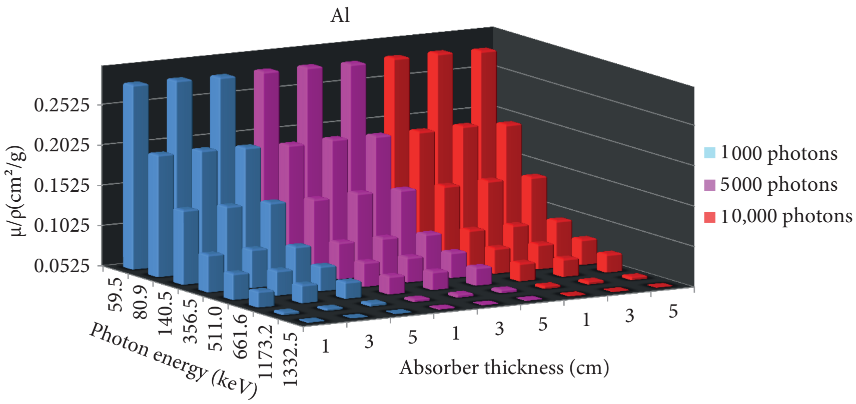

Figure 1. Obtained mass attenuation coefficients vs. different photon energies, absorber thicknesses, and photon numbers for Al (ρ = 2.70 g/cm^3).

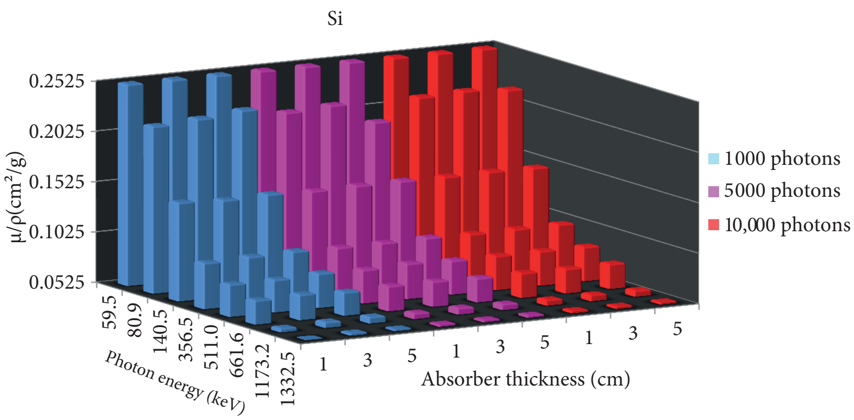

Figure 2. Obtained mass attenuation coefficients vs. different photon energies, absorber thicknesses, and photon numbers for Si (ρ = 2.33 g/cm^3).

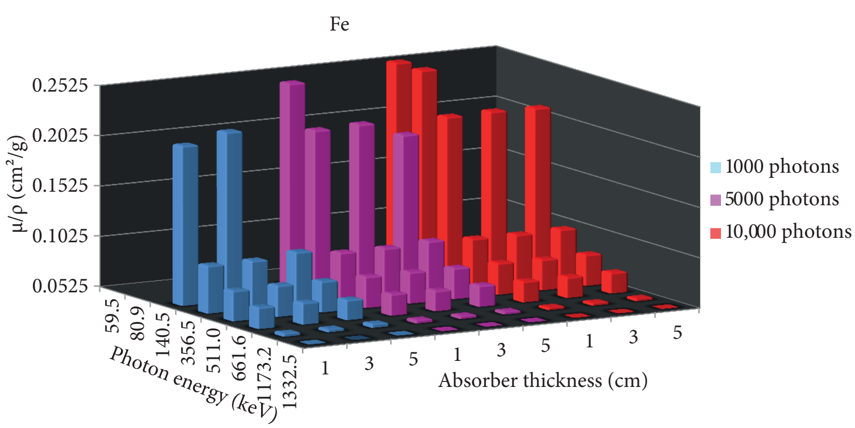

Figure 3. Obtained mass attenuation coefficients vs. different photon energies, absorber thicknesses, and photon numbers for Fe (ρ = 7.87 g/cm^3).

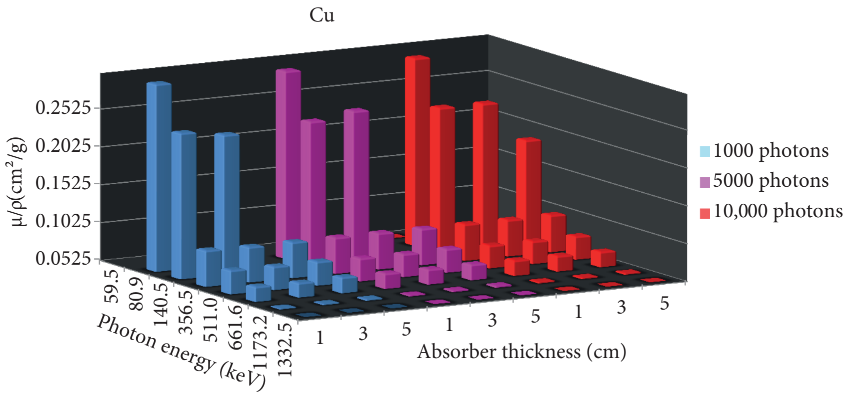

Figure 4. Obtained mass attenuation coefficients vs. different photon energies, absorber thicknesses, and photon numbers for Cu ($\rho = 8.96$ g/cm^3).

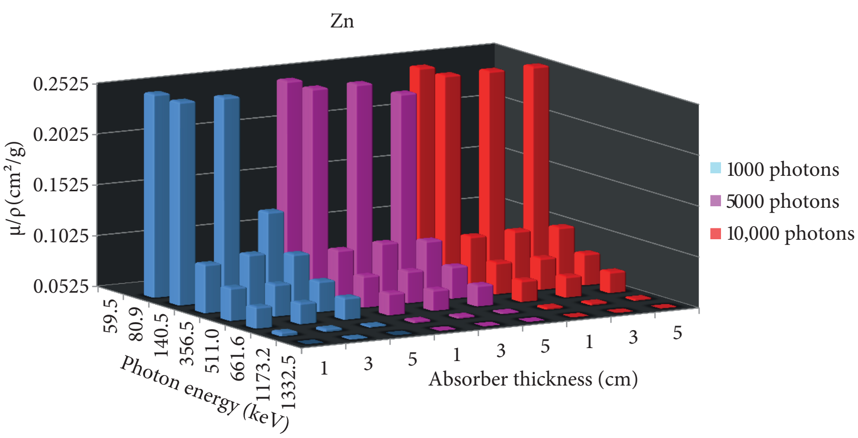

Figure 5. Obtained mass attenuation coefficients vs. different photon energies, absorber thicknesses, and photon numbers for Zn ($\rho = 7.13$ g/cm^3).

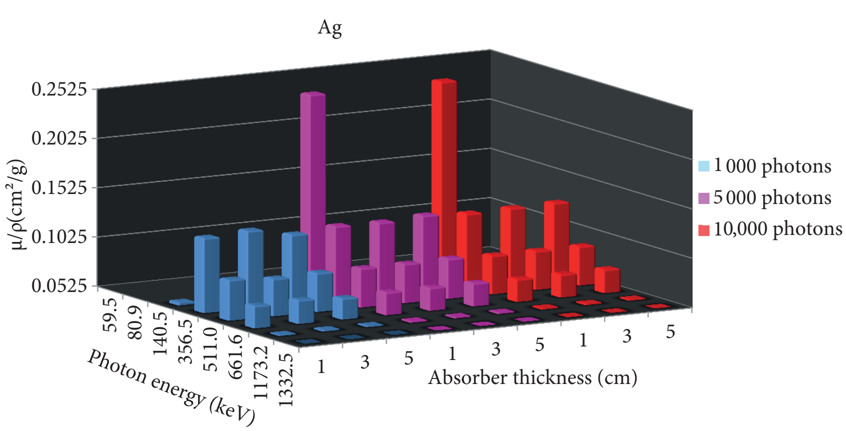

Figure 6. Obtained mass attenuation coefficients vs. different photon energies, absorber thicknesses, and photon numbers for Ag ($\rho = 10.50$ g/cm^3).

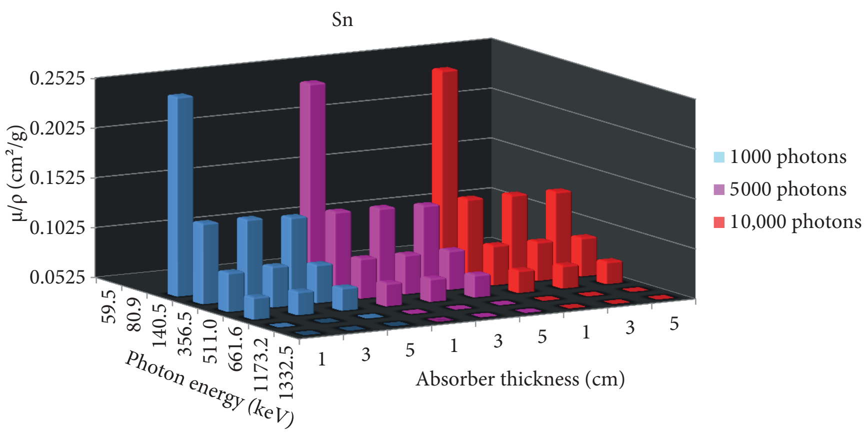

Figure 7. Obtained mass attenuation coefficients vs. different photon energies, absorber thicknesses, and photon numbers for Sn (ρ = 7.31 g/cm^3).

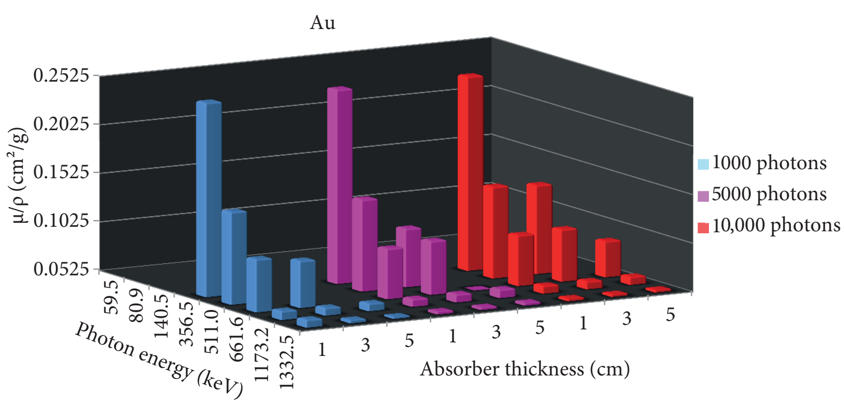

Figure 8. Obtained mass attenuation coefficients vs. different photon energies, absorber thicknesses, and photon numbers for Au (ρ = 19.32 g/cm^3).

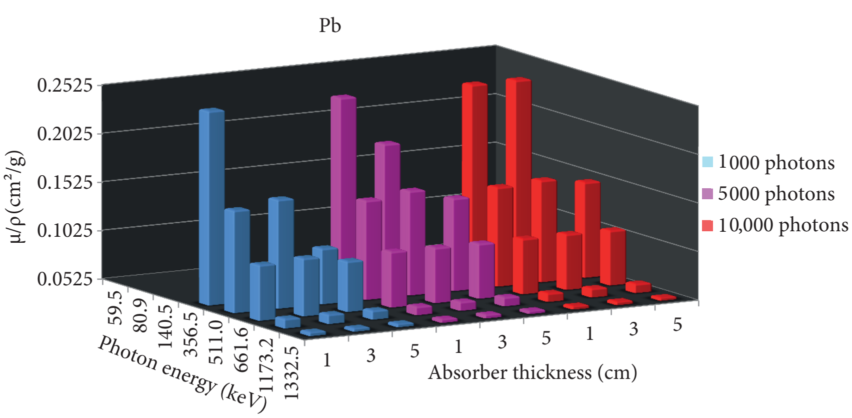

Figure 9. Obtained mass attenuation coefficients vs. different photon energies, absorber thicknesses, and photon numbers for Pb (ρ = 11.34 g/cm^3).

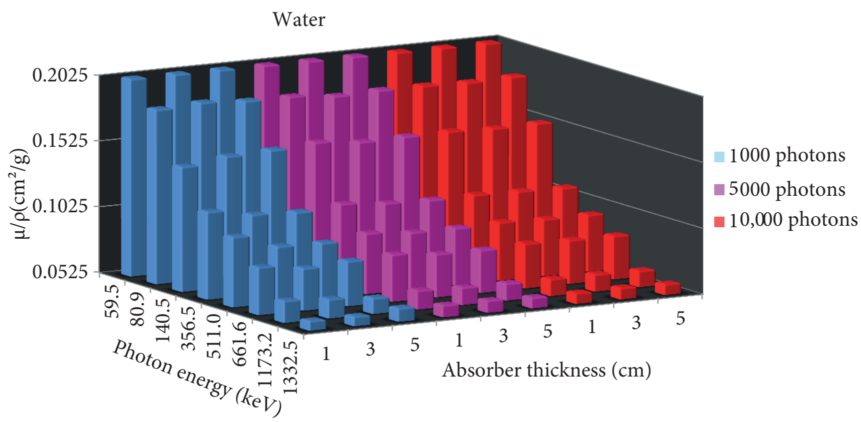

Figure 10. Obtained mass attenuation coefficients vs. different photon energies, absorber thicknesses, and photon numbers for water ($\rho = 1$ g/cm^3).

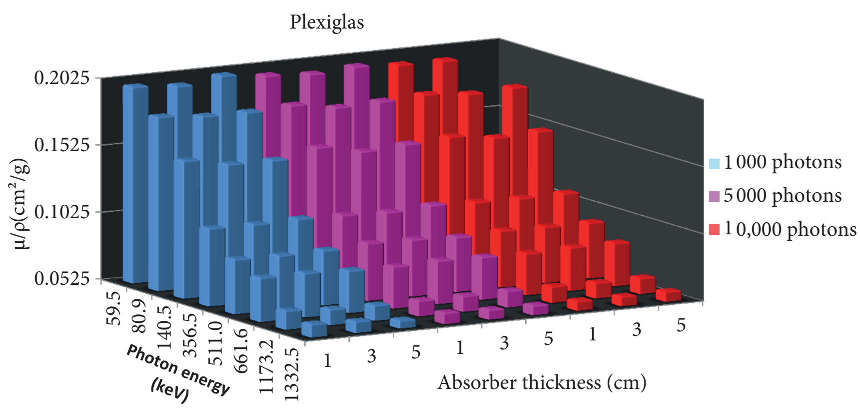

Figure 11. Obtained mass attenuation coefficients vs. different photon energies, absorber thicknesses, and photon numbers for Plexiglas ($\rho = 1.17$ g/cm^3).

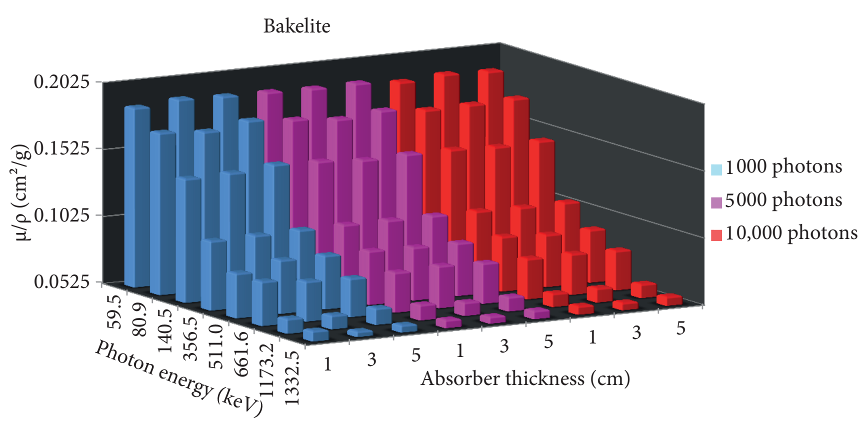

Figure 12. Obtained mass attenuation coefficients vs. different photon energies, absorber thicknesses, and photon numbers for Bakelite ($\rho = 1.15$ g/cm^3).

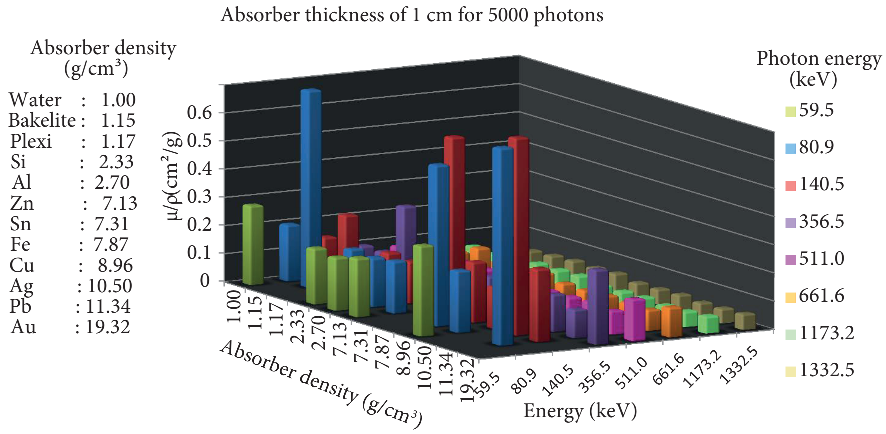

Figure 13. Gamma-ray mass attenuation coefficients vs. photon energies and absorber densities at the absorber thickness of 1 cm.

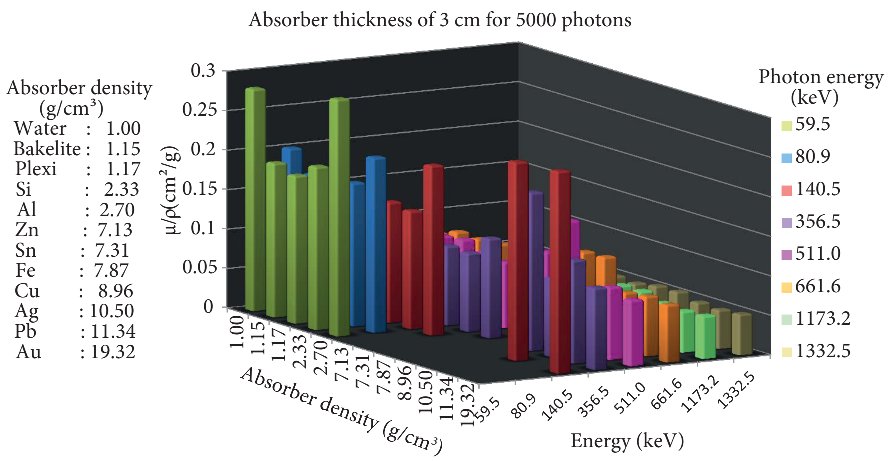

Figure 14. Gamma-ray mass attenuation coefficients vs. photon energies and absorber densities at the absorber thickness of 3 cm.

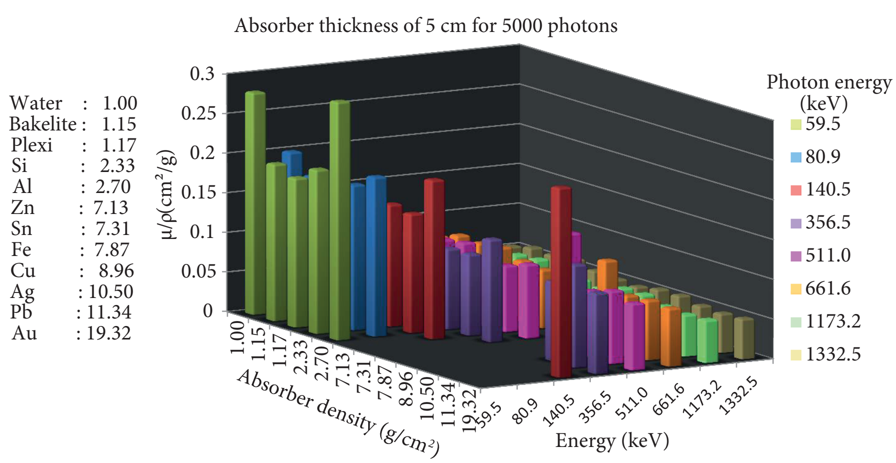

Figure 15. Gamma-ray mass attenuation coefficients vs. photon energies and absorber densities at the absorber thickness of 5 cm.

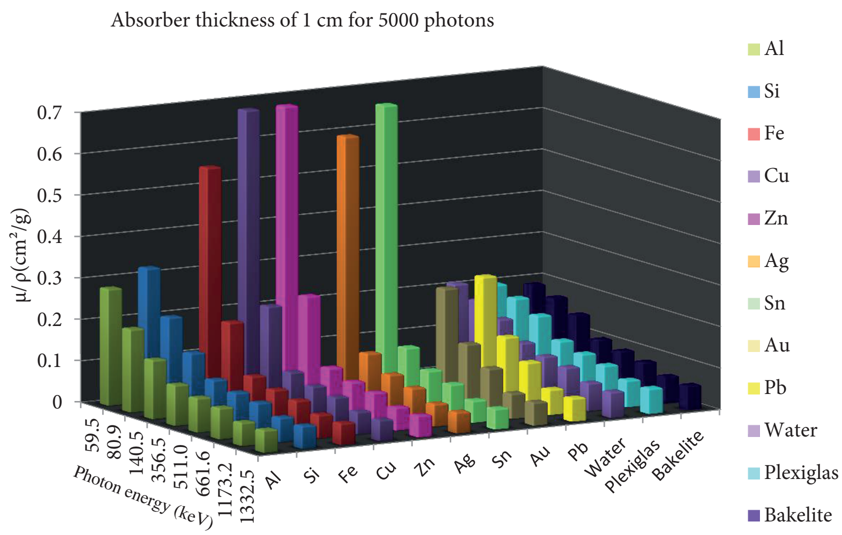

Figure 16. Gamma-ray mass attenuation coefficients vs. photon energies at the absorber thickness of 1 cm.

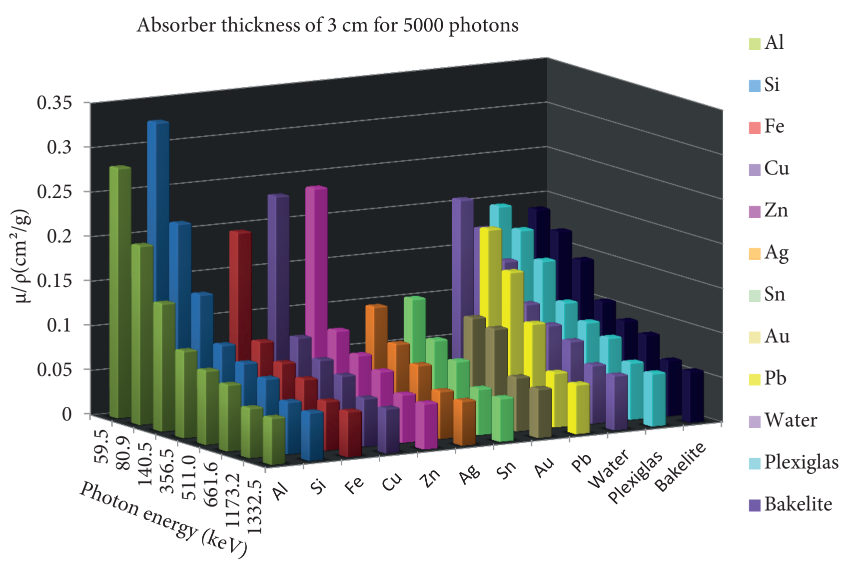

Figure 17. Gamma-ray mass attenuation coefficients vs. photon energies at the absorber thickness of 3 cm.

4. Discussion

The gamma-ray mass attenuation coefficients of Pb, Al, Cu, Plexiglas, Bakelite, Fe, Sn, Zn, water, Si, Ag, and Au materials were determined by using FLUKA MC and XCOM. Different gamma photon numbers (1000, 5000, 10,000) and absorber thicknesses (1, 3, 5 cm) were chosen to investigate how these quantities affect mass attenuation coefficient results in FLUKA differently from the previous studies. The results obtained from the program showed that they were highly in accordance with the literature and NIST values. It can also be recognized that the incident gamma photon number is effective in the calculation results (Tables 2–13). For Au, for instance, the mass attenuation coefficient could not be calculated for 1000 incident gamma photons at 661.6 keV but this value could be found for 5000 and 10,000 gamma photons with the same thicknesses. It is concluded from this result that high incident gamma photon numbers should be used for the FLUKA calculation especially for high-density and high-atomic number materials in order to obtain theoretical results more consistent with the literature values.

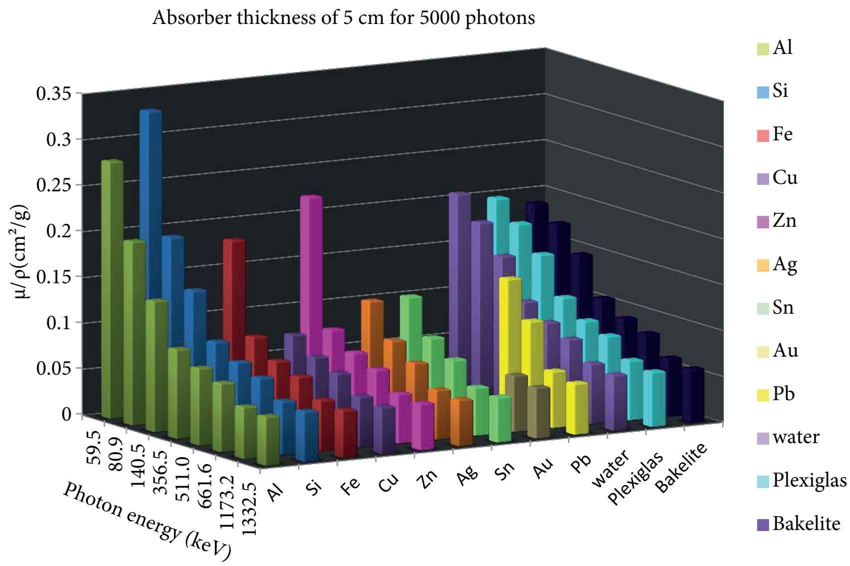

Figure 18. Gamma-ray mass attenuation coefficients vs. photon energies at the absorber thickness of 5 cm.

The gamma-ray mass attenuation coefficients of the absorber materials used were also calculated using XCOM. It was noted that the coefficients from FLUKA were highly in accordance with XCOM results especially for 10,000 photons (Tables 2–13). This result supported the conclusion above that high photon number was suggested in FLUKA for mass attenuation coefficient calculations.

The goal of this work was to indicate the validity of the FLUKA program for the calculation of mass attenuation coefficients. For this purpose, calculations of the mass attenuation coefficients in a wide atomic number, density, and gamma ray energy range were carried out in this study. The mass attenuation coefficients calculated by FLUKA were also compared to results determined by the XCOM program. The coefficients calculated by using both programs were highly in accordance with the literature and NIST values. Consequently, the FLUKA MC program can efficiently be used as an alternative method to calculate the gamma-ray mass attenuation coefficient.

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